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# AN EXPERIMENTAL STUDY OF THE VAPOR BUBBLE THERMOSYPHON BASED ON THE AUGMENTED YOUNG-LAPLACE EQUATION



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# I. INTRODUCTION

As outlined in the bar graph presented in Section IV, the experimental studies can be divided into equilibrium and non-equilibrium studies of the CVBT. We note that we have changed the name of the experimental design from VBT to CVBT (Constrained Vapor Bubble Thermosyphon) which is more descriptive. The equilibrium studies have progressed to the point where we can present our results and project the future course of the research. The details of the experimental results are presented in [P1, P2 & J2] listed under Papers and Presentations. Based on these results we can make the following conclusions:

1) The use of an image analyzing interferometer, IAI, with a constrained vapor bubble thermosyphon, CVBT, was demonstrated under equilibrium conditions at 1g.

2) Using the augmented Young-Laplace equation good agreement between the theoretical and experimental values of the dispersion constant was obtained.

3) A gravitational field restricts the range of forces that can be studied because the curvature gradient, K', is a function of gravity.

4) Ground based studies indicate that a relatively "simple" flight experiment can be designed to evaluate the augmented *equilibrium* Young-Laplace equation using the CVBT.

5) A flight experiment for (at least) a study of the augmented *equilibrium* Young-Laplace equation is warranted.

6) Ground based non equilibrium experiments are being developed.

During this past 6 months, the paper listed under (J2) was submitted to the AIChE Journal. The questions raised by the review process appear to be straight forward and we are in the process of answering them. When the revised manuscript has been accepted for publication, we will deposit copies with NASA. We have also ordered a customized microscope which will allow us to optimize the experimental optical studies. It should arrive by the end of September.

We have also decided to use quartz as the preferred material for the optical cell because of the manufacturing problems associated with making the cell out of a special glass with a high index of refraction. This will put some restrictions on the range of fluids we can study because of the need to have a significant difference between the indices of refraction of the glass and fluid.

# II. PAPERS & PRESENTATIONS

**JOURNALS:**

**J1)** "An Augmented Young-Laplace Model of an Evaporating Meniscus in a Micro-Channel with a High Heat Flux", Manuscript accepted for publication in the International Journal of Experimental Heat Transfer, Thermodynamics, and Fluid Mechanics.

**J2)** "Interfacial Force Field Characterization in a Constrained Vapor Bubble Thermosyphon" S. DasGupta, J. L. Plawsky, and P. C. Wayner,Jr., Manuscript submitted to the AIChE Journal.

**PROCEEDINGS:**

**P1)** "Interfacial Force Field Characterization of a Constrained Vapor Bubble Thermosyphon Using IAI", To be published in the proceedings of the 2nd Microgravity Fluid Physics Conference, Cleveland, OH, June 21-23, 1994.

**P2)** "Determination of the Dispersion Constant in a Constrained Vapor Bubble Thermosyphon" S. DasGupta, J. L. Plawsky, and P. C. Wayner,Jr., Manuscript accepted for the Proceedings of the 4th ASME/JSME Thermal Engineering Conference, Lahina, Hawaii, March 19-24,1995.

**PRESENTATIONS:**

**PR1)** "Thermal Effects in the Spreading of a Liquid Film with a Finite Apparent Contact Angle" P.C. Wayner,Jr., presented at the 1993 APS Meeting, Washington, DC, April 12-15, 1993.

**PR2)** P1 listed above was presented.

**PR3)** P2 listed above will be presented.

**PR4)** "Determination of the Hamaker Constant in an Extended Meniscus Using Image Processing" S. DasGupta, J. L. Plawsky, and P. C. Wayner,Jr., Abstract accepted for presentation at the 1994 Annual Meeting of A.I.Ch.E., San Francisco, CA, Nov. 13-18, 1994.

**THESES:**

**T1)** Staples, L. E., Jr., M. S. Thesis, "An Energy Balance for the Vapor Bubble Thermosyphon", Rensselaer Polytechnic Institute, Troy, NY, August, 1994.

## III. RESEARCH STATUS

**1. Experimental study of the CVBT at equilibrium.** The results of these studies are listed above.

**2. Preliminary theoretical study of the CVBT.** A preliminary simple one dimensional conduction model of the CVBT has been developed. The objective is to determine the approximate operating characteristics of the experimental CVBT. These studies are needed to both initiate our complementary theoretical research and to evaluate our current experimental results. Numerical results are being analyzed and numerical modifications are being developed.

**3. Development of data analysis codes.** These codes are being developed as needed.

**4. Design and construction of a CVBT test cell for non equilibrium studies.** The experimental objective for this ground based definition study of the constrained vapor bubble thermosyphon (CVBT) is to optically study the performance of an evaporating, three dimensional extended meniscus in a square micro-channel. The thermophysics of the CVBT were described in the proposal and the manuscripts listed above. In small systems, the interfacial intermolecular force field, in conjunction with the capillary and surface forces can be used to control fluid flow and heat transfer. The pressure field, which is a function of the liquid thickness profile, will be evaluated using image analyzing interferometry (IAI). The following provides a concise description of the design considerations and description of the CVBT. *Although the CVBT is in the final stages of development, we experienced difficulties with the new glass.* Our special glass cell proved to be too brittle, which showed up in the cleaning procedures. Although this special glass is **not** an essential part of the ground based studies, the high index of refraction is certainly a plus. For now, we have decided to use the initial type of glass we evaluated: quartz.

Figure 1 is a diagram of the cell to be used as the CVBT. The diagram is not to scale. The material of construction for the heat transfer cell is glass to facilitate optical observation and measurement of the evaporating liquid meniscus. In order to see the interferometric fringes of a liquid film on a solid substrate, the refractive indexes of the liquid and solid should be substantially different. For glass (ordinary or quartz) and alkanes (the liquids we are planning to use because of their non-polar nature), the difference is small for higher molecular weight alkanes and the fringes are not as distinct as we would like for accurate measurement. Hence a special high refractive index glass (Schott glass SFL6) was evaluated as the CVBT material to ensure high contrast for the fringes. However, we had too many manufacturing problems with the specialty glass. Now we plan to keep the molecular weight of the alkanes low so that we can use quartz which is easier to fabricate.

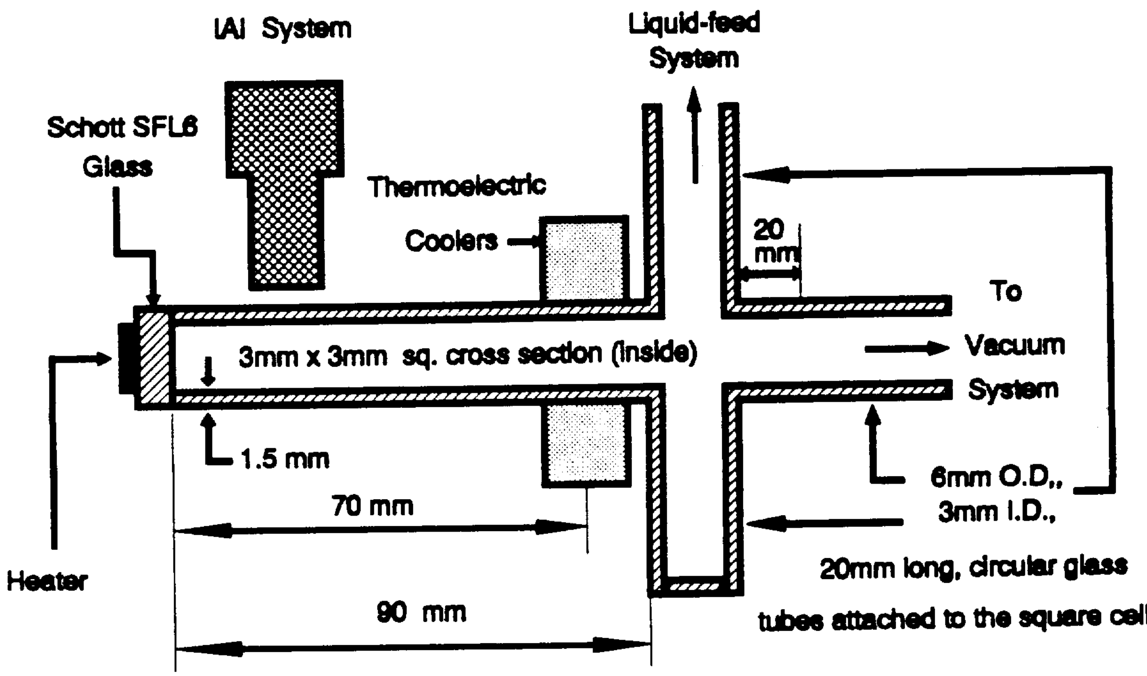


Figure 1. Schematic Diagram of the Vapor Bubble Thermosyphon.

As can be seen from Fig. 1, the cell is square (3mm x 3mm inside) in cross section, with an active length of about 70mm (depending on the glass, shorter lengths are also possible), where in addition to the intermolecular force field gradients, the four corners will facilitate the flow of liquid towards the hot spot (the evaporator) due to capillary suction. The CVBT designed herein is essentially a long heat pipe with square cross section and can be divided into three sections - the evaporator, the adiabatic mid-section and the condenser. At one end of the CVBT, heat will be added to the system, using a small resistance heater. Liquid will evaporate from that region and the generated vapor will carry the heat towards the condenser, where it condenses, releasing the latent heat, and the condensed liquid flows back to the evaporator. We have successfully tested the viability of this concept using a commercially available micro fluorimeter quartz cell with the inside dimension of 3mm x 3mm x 43mm.

In the condenser part, four miniature (5 mm x 5mm x 2.4mm) thermoelectric cooler will be attached to the four sides of the CVBT and connected to a power supply in parallel. The coolers are highly reliable solid state thermoelectric heat pumps and the advantages of using them with our cell are their small sizes, low weight and their capability of adjustable, quick cooling to below ambient temperature. As a result, we will be able to precisely control the condenser temperature. The heat sink (an aluminum block with an adjustable square channel to accommodate the coolers and the cell) for the coolers is designed to act as a holder for the whole CVBT assembly. Small thermocouples will be attached on the outside wall of the CVBT to measure the temperature field present in the CVBT as well as the condenser temperature.

Cleaning the cell is a critical step in the effective and meaningful characterization and modeling of CVBT performance, since the intermolecular force field is very sensitive to the presence of impurities in the system. We have designed a vacuum system and developed a wet cleaning technique. Initially the cell will be immersed in a hot (70 C) 1:1 solution of hydrogen peroxide (30%) and ammonium hydroxide for about 5 minutes. This will remove the organic impurities adsorbed on the glass surface. After that the cell will be rinsed thoroughly in deionized distilled water and will be dried in an oven. The cleaning and assembly of the cell will be performed in a class-100 clean hood to minimize the presence of dust particles and readsorption of organic contaminants. It should be emphasized that getting rid of all the dust particles is an extremely difficult proposition and some modifications of the present cleaning technique may be required in the future.

Of the three tubes attached to the CVBT (as shown in Fig. 1), one will be connected to a vacuum pump through a high vacuum valve and cold trap, another will be attached to a liquid feed system through another high vacuum valve. The third tube will be kept closed. At the beginning of the experiment, the liquid feed chamber (not shown in the figure) will be filled with pure test liquid, but the liquid feed valve to the CVBT will be kept closed. The cell will then be subjected to a high vacuum (less than 30 millitorr) to remove any water vapor adsorbed on the inside glass surface, since adsorbed layers of water can significantly alter the surface energy of a solid substrate. After a sufficiently long time, the vacuum valve will be closed and the liquid feed valve will be opened slowly so that the cell will be filled with a mixture of the working liquid and its vapor and the experiment will be started. The heat input to the system at the evaporator and the heat taken out at the condenser will be controlled by controlling the voltage and/or current to the heater and the thermoelectric coolers respectively.

We have designed and ordered the cell and the accessories for the set up. We have already received most of our parts and assembled the vacuum system, liquid feed arrangements, coolers, heat source and temperature measurement systems. As far as the film thickness measurement procedures are concerned, we have decided to use image analyzing interferometry. In that method, relative reflectivity at each point of a captured picture will be measured using our image processing set up and by analyzing the relative reflectivites, film thickness at every pixel will be determined. The interferometer, CCD camera and the image processing set up are already in place and we have developed and/or modified the necessary computer programs and tested them with our prototype cell to measure the film thickness profiles of a liquid inside the CVBT as a function of the evaporation rate. During this period, we have also ordered a customized microscope which will allow us to optimize the experimental optical studies.

# CVBT RESEARCH PLAN